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NEW MODELS OF ABUNDANCE STRATIFICATIONS IN THE ATMOSPHERES OF MAGNETIC AP STARS

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Abstract. The atmospheres of magnetic Ap stars (chemically peculiar stars) are supposed to be inhomogeneous in chemical abundances. This prediction of the atomic diffusion hypothesis is confirmed by recent observations. However, numerical modelling of these stratifications is very difficult, especially for atmospheres with strong magnetic fields. We present here preliminary results of abundance stratifications (equilibrium solutions) obtained for the first time by detailed calculations including magnetic fields.

1 Introduction

Chemically peculiar stars on the upper main sequence are characterised by large over-abundances of certain metals. Many of these stars are permeated by strong magnetic fields (some 1 kG to 35 kG) and for those stars, surface abundance inhomogeneities are correlated with the magnetic structures. Atomic diffusion is considered to be at the origin of these abundance anomalies (Michaud 1970).

Magnetic fields affect the diffusion of ions. For instance, Vauclair et al. (1979) considered the upward diffusion of Si I that would produce overabundances in magnetic Ap stars at places where the magnetic field is horizontal (Alecian & Vauclair 1981). This behaviour is due to the low diffusion velocity of Si ions, and the high upwards diffusion velocity of neutral Si. On the contrary, gallium is thought to accumulate near vertical field regions (Alecian & Artru 1987). Concerning observations, Zeeman-Doppler-Imaging (Kochukhov et al. 2004) is beginning to provide simultaneous magnetic *and* abundance maps for several elements.

Radiative acceleration, which is an important quantity in the determination of the diffusion velocities, is shown to be quite sensitive to blending, magneto-optical effects, and the Zeeman patterns of the lines involved. Alecian & Stift (2004, 2006) investigated in detail the magnetic amplifications of radiative accelerations and diffusion velocities of a large number of chemical elements as a function of field strength and of field direction. In the present talk, we consider first results of detailed modelling of abundance stratifications in atmospheres of magnetic Ap stars.

2 Diffusion and magnetic fields

Magnetic fields modify atomic diffusion in two ways. Charged particles are strongly constrained to follow field lines; this affects the contribution of ions to the diffusion velocity of the element. Radiative accelerations are also modified by Zeeman splitting of absorption lines.

2.1 Effects on diffusion velocities

An approximate theory of diffusion in magnetic fields can be found in Chapman & Cowling (1970). The diffusion velocity of charged particles, orthogonal to magnetic lines, is reduced by the factor:

$$f_{slow,i} = \left(1 + \omega_i^2 t_i^2\right)^{-1}, \tag{2.1}$$

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where t_i is the collision time (the time taken by a particle i with mass m_i and charge $Z_i e$, to deviate by $\frac{\pi}{2}$ through collisions from its initial motion), $\omega_i/2\pi$ the cyclotron frequency in a field with strength H:

$$\omega_i = \frac{Z_i e H}{m_i c}. \tag{2.2}$$

On the surface of a magnetic star, the direction of the magnetic field lines varies from $\theta = 0$ to $\frac{\pi}{2}$ between magnetic pole(s) and equator. In magnetic fields that are neither strictly horizontal nor strictly vertical, the diffusion velocity vector is inclined with respect to the vertical. This inclination is given by the expressions first derived by Alecian & Vauclair (1981) and schematised in Fig.1. The vertical (z-axis) component is (Alecian & Stift 2006):

$$V_{Hz,i} \approx V_{D_i} \left[f_{slow,i} + (1 - f_{slow,i}) \cos^2 \theta \right], \tag{2.3}$$

There is also a horizontal component of the diffusion velocity which can have the same order of magnitude as the vertical one, but it has a very small effect on the horizontal distribution of elements. Because of the much smaller vertical height scales, vertical diffusion leads to observable effects much earlier (by several orders of magnitude) than horizontal diffusion. The latter can thus be neglected here.

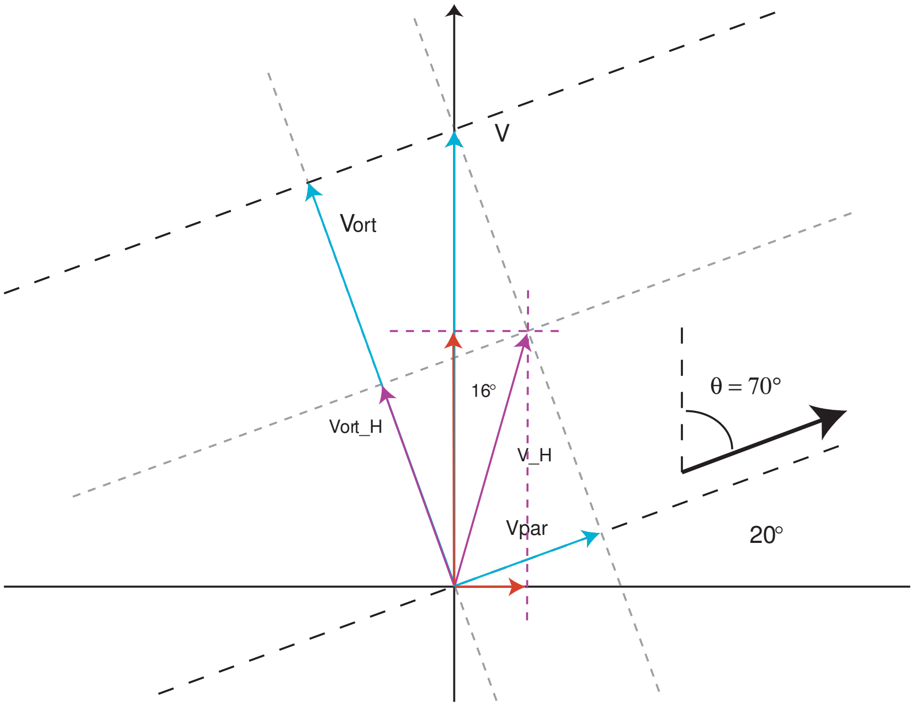

Fig. 1. Diffusion velocity for inclined magnetic fields, here for $\theta = 70$ deg. Only the velocity component (V_{ort}) orthogonal to the magnetic lines (long-dashed) is reduced to V_{ort_H} by factor f_{slow}.

2.2 Zeeman amplification of the radiative accelerations

An ion A^{+i} is radiatively accelerated both through bound-bound transitions and through bound-free transitions (photoionisations) of the ion $A^{+(i-1)}$. In the presence of magnetic fields, the former contribution is subject to an amplification effect due to Zeeman splitting of the lines. As shown by Alecian & Stift (2004), this amplification cannot be neglected. These authors developed the code CARAT which computes in detail the radiative accelerations of a large number of chemical elements as a function of field strength and of field direction. The code carries out full opacity sampling of Zeeman split spectral lines and determines the radiative flux by solving the polarised radiative transfer equation. In a recent work (Alecian & Stift 2006), accelerations due to bound-free transitions have been included in CARAT which takes into account the momentum redistribution effect and computes the diffusion velocities.

3 Computation of abundance stratifications

The knowledge of diffusion velocities is, of course, essential to the modelling of abundance stratifications in stars. The abundance stratification process is described by the solution of the time-dependent continuity equation for element concentrations. However, in stellar atmospheres (where radiation transfer must be carried out in detail for each time-step), such computations are presently beyond computing possibilities even for the non-magnetic case. To overcome this difficulty, one can look for stationary solutions for each element. For instance, since radiative accelerations are very sensitive to element concentrations, one may search for an abundance stratification such that radiative accelerations are equal to gravity everywhere in the atmosphere (equilibrium solution). Such a solution does not necessarily exist, and if it exists, there is no reason to believe that it will be unique in optically thin media. Such solutions have been computed by Hui-Bon-Hoa et al. (2000), and by LeBlanc & Monin (2004) for non-magnetic atmospheres.

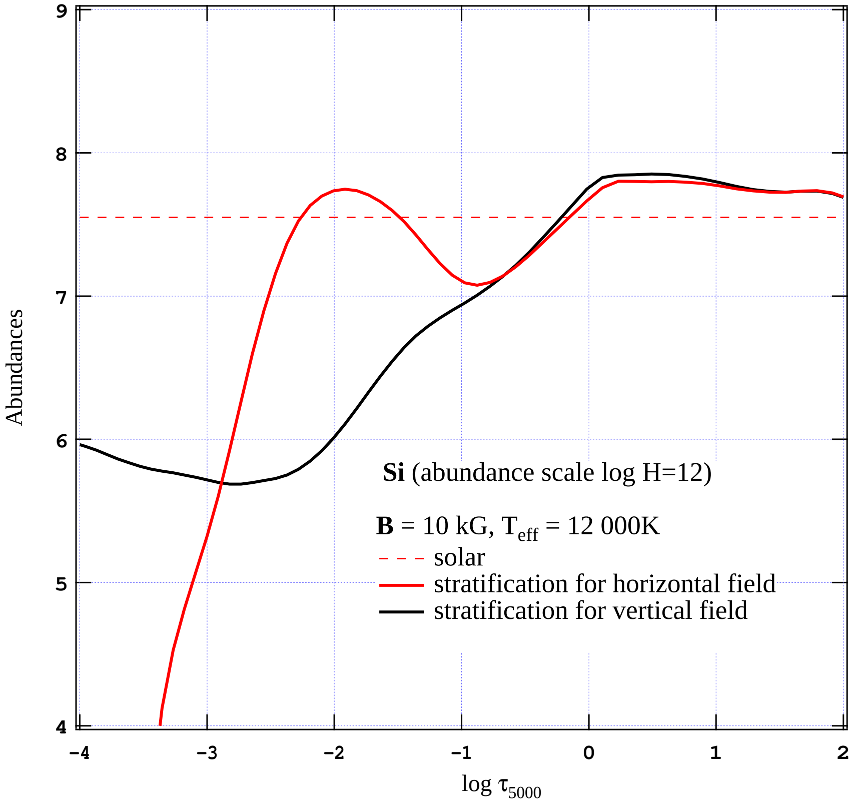

Fig. 2. Abundance stratification (equilibrium solution) of Si in a magnetic atmosphere. Computations have been carried out for a main sequence star with $T_{\rm eff} = 12000\,$K, and a 10 kG magnetic field. The black curve is for a vertical field, the red one for a horizontal field. The abundance is given relative to hydrogen with $\log \mathrm{H} = 12.0$.

We present here a preliminary result concerning equilibrium solutions for silicon in magnetic atmospheres. The diffusion velocities are computed by our CARAT code, and an equilibrium solution for stratification is obtained through an iterative procedure which is still in a development phase. Figure 2 shows the abundance of Si with respect to the optical depth, for a main sequence star with $T_{\rm eff} = 12000$K, with a 10 kG magnetic field (vertical and horizontal field lines). One can notice that, in the case of a vertical field, Si does not accumulate above $\log \tau = 0.0$. In the case of a horizontal field, a cloud of Si is formed around $\log \tau = -2.0$. Such a stratification pattern should lead to observably different silicon abundances near the magnetic pole(s) compared to the equator. Si is expected to be more abundant at the magnetic equator. This is consistent with the theoretical predictions made by Vauclair et al. (1979) and by Alecian & Vauclair (1981). However, the detailed process seems to be more complex than supposed previously, because the cloud of Si for a horizontal field is partly due to the *hole* around $\log \tau = -1.0$. Indeed, the decrease in Si abundance around $\log \tau = -1.0$ makes photons available to the upper layers which then support the cloud. This kind of effect cannot be observed in stellar interiors which are optically thick.

4 Conclusions

Thanks to recent improvements and extensions to our CARAT code which is now able to compute diffusion velocities in magnetic atmospheres, we have started to model equilibrium abundance stratifications of metals in magnetic stars. This kind of modelling is carried out for the first time. We have presented preliminary results for silicon, but our purpose is to calculate surface abundance maps for more metals. One can envisage that, in a near future, it will be possible to confront model predictions of surface abundance inhomogeneities of magnetic Ap stars to observations.

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